Using Telemetry to Navigate the MarCO cubesats to Mars

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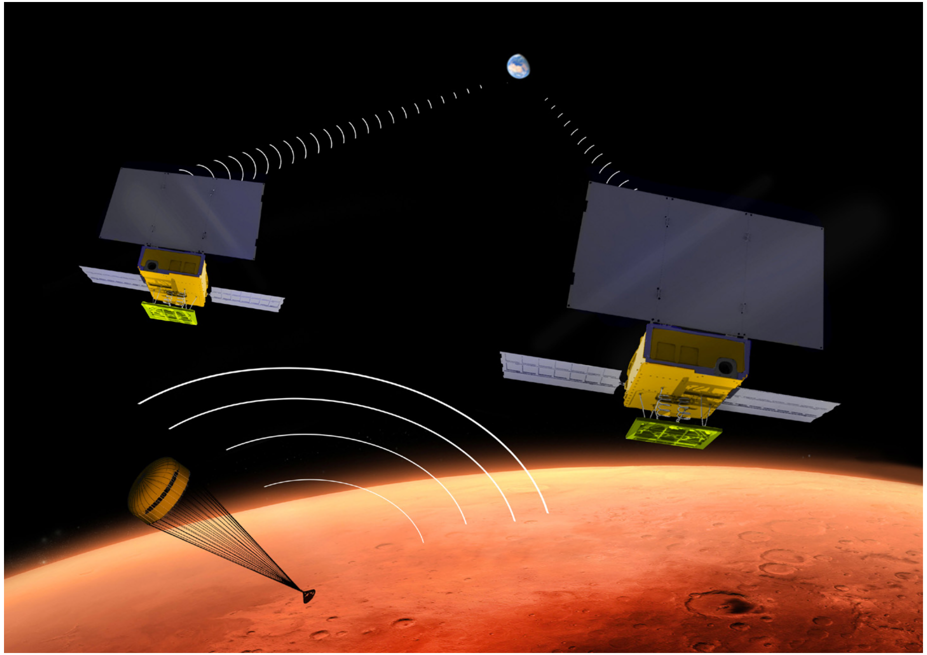
Introduction

MarCO Mission Overview

- Twin 6U CubeSats launched alongside InSight in May 2018
- Primary mission to demonstrate interplanetary CubeSat technologies
  - IRIS radio
  - Navigability
  - Ability to perform Trajectory Correction Maneuvers (TCMs)
- Nominal mission to provide real time relay of Insight Entry, Descent, and Landing (EDL)

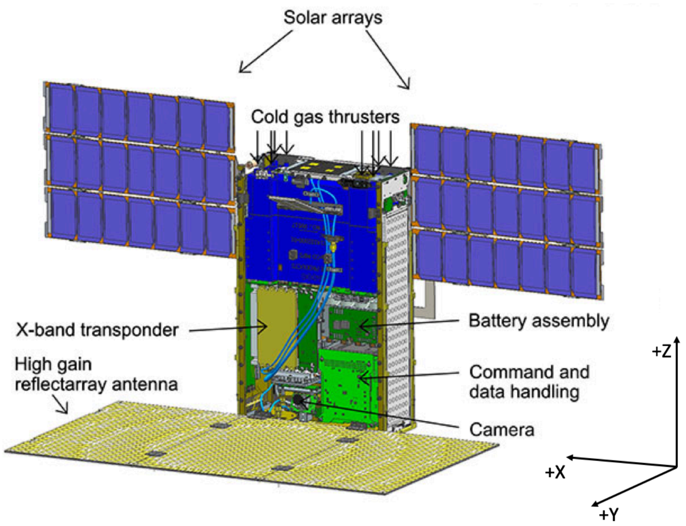


Unique Aspects of MarCO requiring telemetry

- Similar to larger spacecraft
  - Data types Doppler, Range, and ΔDOR
  - Shorter passes due to power constraints
  - High number of ΔDOR using InSight opportunities

- Maneuvers implemented using simple cold gas system
  - Accurate maneuvers depended on accurate thruster modeling
  - Wheel-speed telemetry used to improve knowledge of thrusters from start of mission

- MarCO-B Launched with two leaks
  - Leaks themselves led to significant thrusting
  - Mitigation techniques resulted in large number of small ΔVs
  - Significant telemetry processing required to generate reliable orbit determination (OD) solutions during cruise



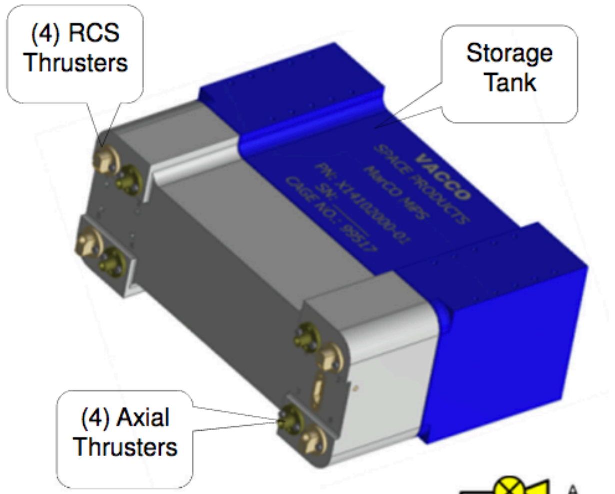
Wheel-speed Derived Thruster Values

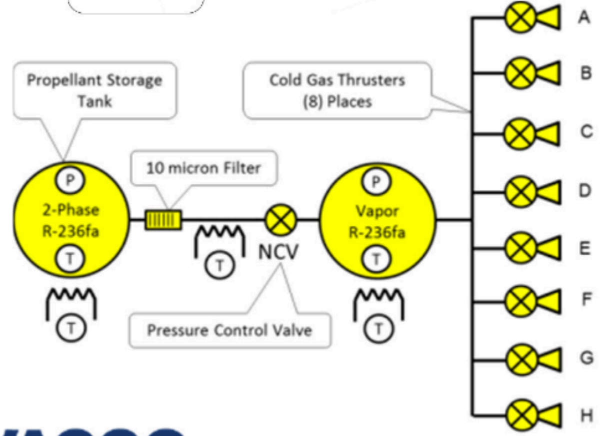
MarCO Thruster System

- Cold gas propulsion system provided by VACCO
  - Integrated storage tank
  - 4 Trajectory Correction (TCM) thrusters (B, C, F, G)
  - 4 Attitude Control thrusters canted 60° (A, D, E, H)
  - Approximately 40 sec specific impulse
  - Each thruster ~25±10 mN

- Integrated XACT Attitude Control system (ACS) provided by Blue Canyon Technologies

- Maneuvers implemented by:
  - Opening tank-to-plenum valve to regulate to known pressure
  - Commanding spacecraft to specified TCM attitude
  - Commanding ACS system to duty cycle plenum-to-space valves (thrusters) for a specified number of thruster seconds
  - ACS controls duty cycle to maintain attitude during TCM



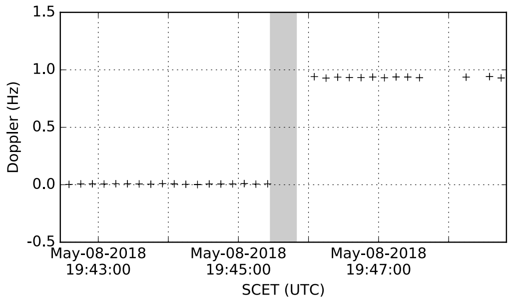


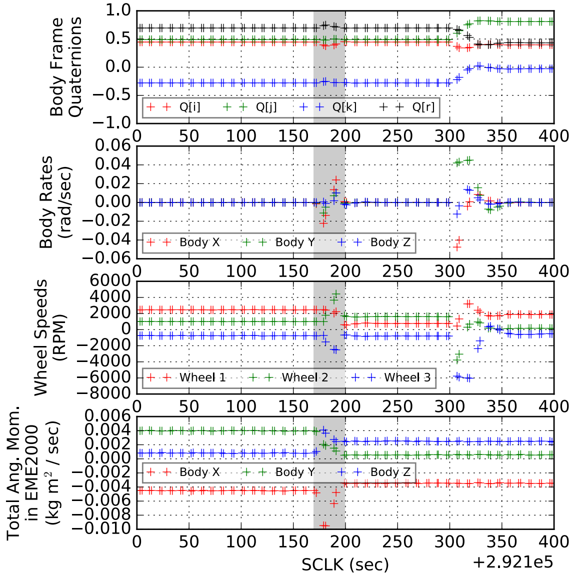
Thruster Calibration Design

- In order to perform initial maneuver design needed:
  - Approximate thrust level of each thruster
  - Expected duty cycle at steady state
- Did not want to perform thruster calibration long enough to get to steady state
- Executed three 10-second burns, mutually orthogonal and 55° from earth line, visible on low gain antenna (LGA).
- Recorded thruster counts and reaction wheel speeds from telemetry (no accelerometer available)
- Executed on A soon after launch

Thruster Calibration Data and Processing

- Estimated thrust levels for each thruster and center of mass
- Used Doppler to observe total applied ΔV on earth line
- Used wheel speed change as measurement of applied torque
  - Wheel speeds measured at non-rotating times to remove noisy body rate data effects
- Implemented in normal OD batch filter with low-fidelity models of actual thrusting event
- **Note:** This technique does not yield significant new information on total ΔV. It only helps differentiate the individual components.





Thruster Calibration Results and Performance

Thruster	TCAL-A1 (mN) Force	TCAL-A1 (mN) 1σ	TCAL-A2 (mN) Force	TCAL-A2 (mN) 1σ	TCAL-A3 (mN) Force	TCAL-A3 (mN) 1σ
A	24.1	2.3	45.7	8.7	24.4	9.7
B	11.4	4.0	10.2	3.3	14.7	3.1
C	26.0	3.6	27.9	3.1	21.2	2.8
D	26.4	10.0	29.2	10.0	25.4	10.0
E	22.5	2.4	16.9	8.7	29.4	9.7
F	35.2	7.3	33.7	5.3	35.7	6.1
G	45.2	6.1	52.3	5.2	34.5	5.2
H	25.4	2.7	26.1	9.9	26.1	9.9

Estimated thruster levels

Doppler-only yields 7.0 mN uncertainties

A priori uncertainty of 10.0 mN

- Balancing torques gave [90%, 90%, 26.4%, 50.3%] duty cycles
- Expected 1.99 mm/sec^2 ΔV to thruster second conversion
- Actual duty cycles were slightly higher due to RCS thruster usage
- Predictions still helpful in designing initial maneuvers, and demonstrating wheel-based technique

Maneuver Implementations

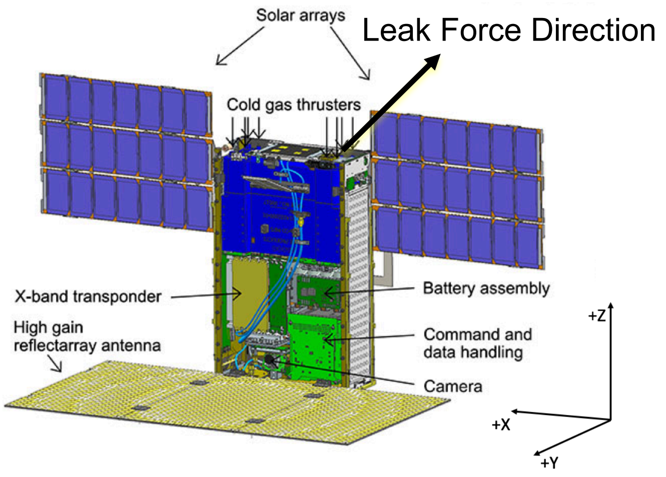
TCM	ΔV (mm/sec)	Thruster Time (sec)	Ratio (mm/sec^2)
TCAL-A1	67.4	30.01	2.247
TCAL-A2	58.9	30.07	1.959
TCAL-A3	54.6	30.03	1.817
TCM-A1x	495.3	253.68	1.953
TCM-A1a	481.2	257.13	1.871
TCM-A1b1	961.0	504.60	1.905
TCM-A1b2	914.5	504.58	1.812
TCM-A1b3	431.6	254.95	1.693
TCM-A1b4	468.6	255.39	1.835
TCM-A1b5	508.2	254.76	1.995
TCM-A1c1	477.2	256.20	1.863
TCM-A1c2	502.3	254.64	1.973
TCM-A1c3	532.0	256.31	2.076
TCM-A1c4	548.9	255.32	2.150
TCM-A1d1	1926.1	972.22	1.981
TCM-A1d2	340.5	194.41	1.752
TCM-A1d3	178.4	90.65	1.968
TCM-A1e	269.8	147.41	1.831
TCM-A2a	247.7	130.30	1.901
TCM-A2b	266.7	130.27	2.047
TCM-A2c	295.7	80.50	3.673
TCM-A3a	215.3	55.77	3.861
TCM-A3b	215.3	51.36	4.192
TCM-A3c	242.2	51.70	4.684
TCM-A3d	242.2	61.74	3.922

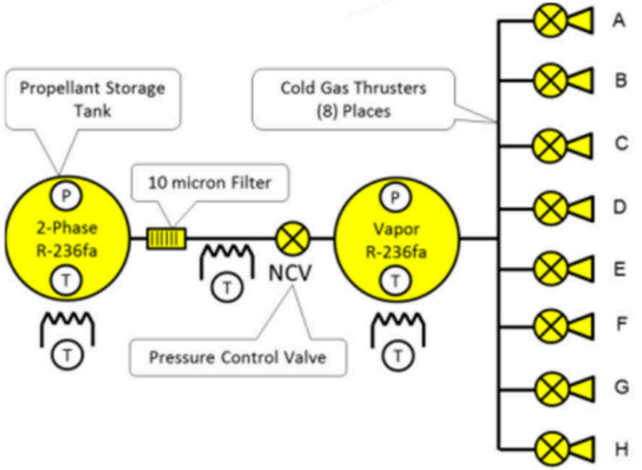
Loss of plenum regulation capability

MarCO-B’s Leak and Telemetry-based Mitigation

MarCO-B's Thruster Leak

- MarCO-B launched with known small leak in pressure control valve
  - Plenum would slowly recharge after use
  - Cycling valve could lead to higher or lower leak level regimes
- Spacecraft in nominal mode oriented +Y axis to sun and spun about that axis every 45 minutes to cancel out solar torques
- First thruster calibration attempt cycled to a higher leak rate
  - Spacecraft reaction wheels began saturating
  - Applied torques indicated that thruster D also had a small leak
- Spacecraft began experiencing wheel-desaturation and tumbling cycles

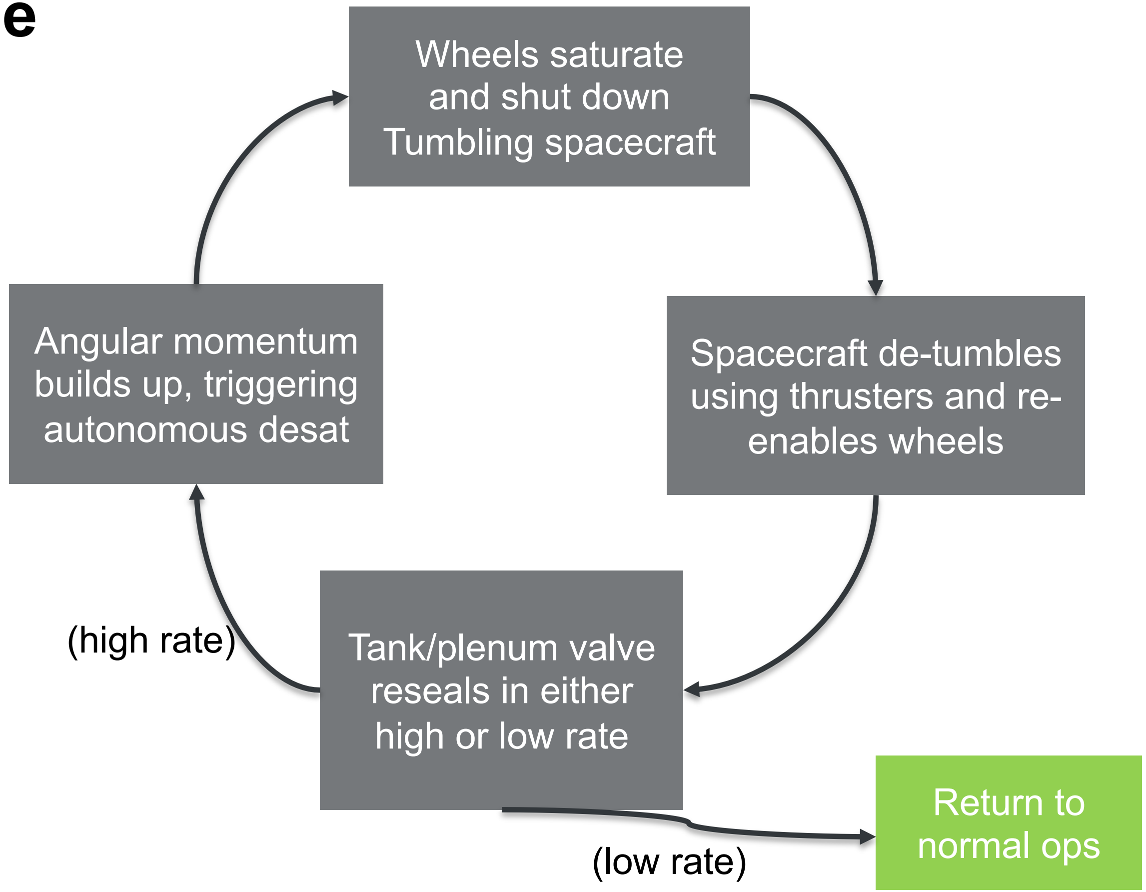




Anatomy of a Wild Ride

"Rotisserie mode" helped cancel out most torque from the thruster leak

However, if the thruster leak was too large, angular momentum would get too large before a rotisserie rotation could complete. This led to a "wild ride"



Leak Mitigation Blowdown Technique

- Spacecraft team quickly implemented a “slow blowdown” (SBLO) method to reduce wild rides
  - Effort to keep plenum pressure low enough to prevent “wild rides”
  - Every 30 minutes would slew to selected attitude
  - Open four TCM thruster valves to release any pressure in the plenum without adding angular momentum
  - Mostly successful, though a high leak rate could saturate wheels before SBLO occurred (4 times after implementation)

- Ultimately led to three OD challenges
  - Constant leak with sun direction rotation
    - Modeled as sun-direction constant acceleration
    - Difficult to estimate due to lack of reasonable a priori values
  - Estimating many small SBLO events
  - Fitting through wild rides with large and uncertain thrusting events
    - Resolved by quickly moving initial epoch past events, and relying on ΔDOR to constrain short arcs

Estimating Leak Level

- The thruster leak could be approximated as sun-direction constant acceleration (aliased with solar radiation pressure)

- Needed an approximate *a priori* value and reasonable range, since we weren't sure of value to an order of magnitude

- Got wheel change speed between SBLOs from telemetry

- Combined with pressure data to get formula for expected accumulated torque as a function of leak size

$$\Delta \ell = \sum_i C_i \left(\mathbf{r}_4 \times \mathbf{d}_4 \right) \left(P_0 + \frac{P_f - P_0}{t_f - t_0} (t_i - t_0) \right) A$$

- Used to compute average accelerations in a least squares filter.
  - Computed an 0.015 mm diameter leak, with 2 μN force
  - Somewhat insensitive to plenum pressure, probably due to higher pressures holding valve closed more
  - Sun direction force varied from 0.1 to 1.0 μN, providing reasonable bounds for OD

- Technique not repeated throughout cruise, since Doppler-based estimates held within reason

Estimating Blowdowns

- SBLOs were hundreds of small ΔVs
  - Initially, did not have good values for timing, attitude or size
  - Difficult to estimate, so instead tried to estimate constant force and accept discontinuities in residuals
  - Constraining direction of these constant accelerations became challenging quickly

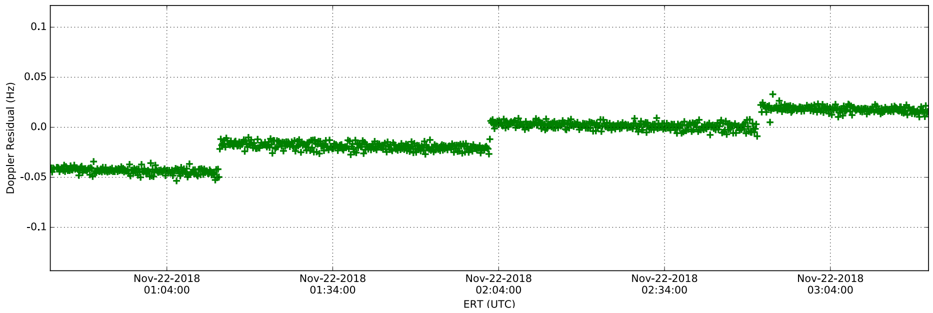
- Instead, data were available in telemetry
  - Times of SBLOs were available as “event records” (EVRs)
  - Attitude quaternion at given SCLK in normal telemetry
  - With known I_{sp} and fixed plenum volume, ΔV could be computed from ideal gas law as:

$$\Delta V = \left(\frac{P_2}{T_2} - \frac{P_1}{T_1}\right) \frac{V}{M} \frac{g I_{sp}}{m_{s/c}}.$$

  - ΔV computation ignores plenum-refilling and potential liquification of propellant

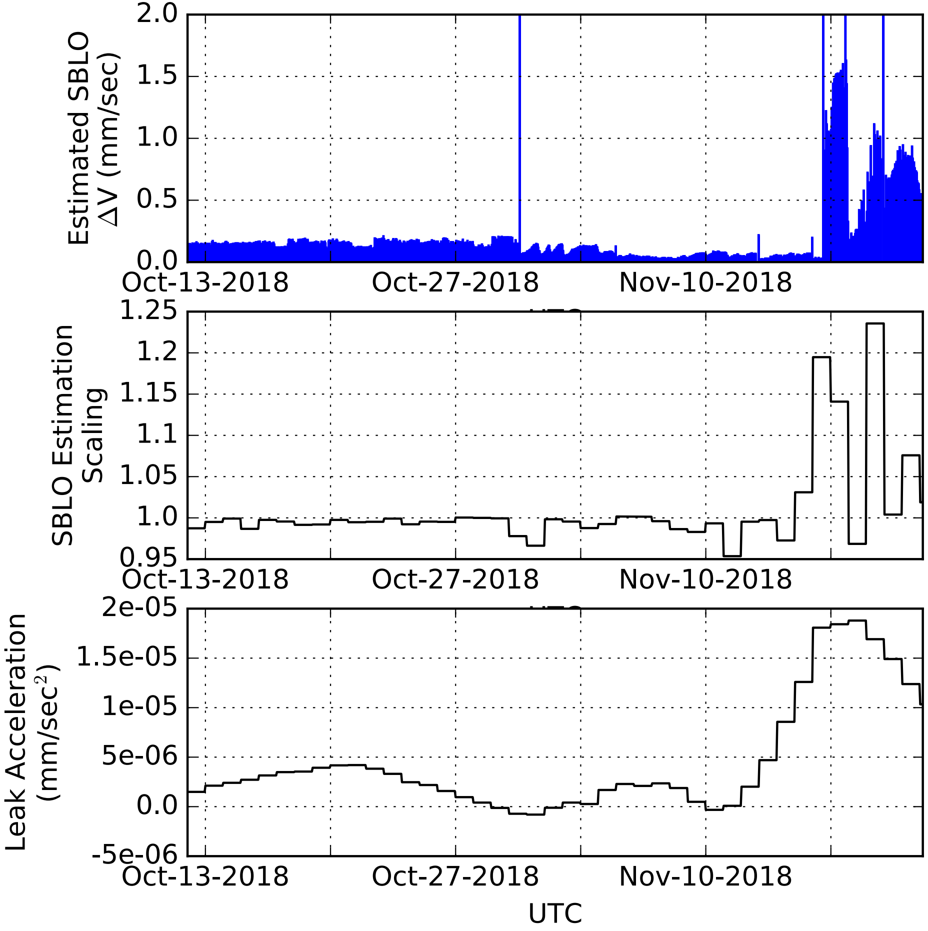
- However, these values were not always available
  - Needed attitude quaternions, and temperature/pressure values at blowdowns
  - Mission control team began collecting that data around SBLOs automatically and prioritizing for downlink
  - Once this change made, getting event records was most unreliable part, so added algorithm to identify pressure drops indicative of a ΔV
  - Have looser inputs for cases where no data are available

- Estimated stochastic scale factor on ΔV, and small off-axis terms with constant size



Leak Estimate Results

- This technique was successful in letting us navigate to Mars with reasonable accuracy
- Had higher scale factors during higher pressures, due to ideal gas assumptions being more inaccurate
- Leak acceleration rates stayed reasonable
- Kept MarCO-B arcs short, moving past ”wild rides” quickly, because it was hard to get good a priori values for those ΔVs
- Large number of ΔDOR measurements helped make short arcs acceptable



Conclusions

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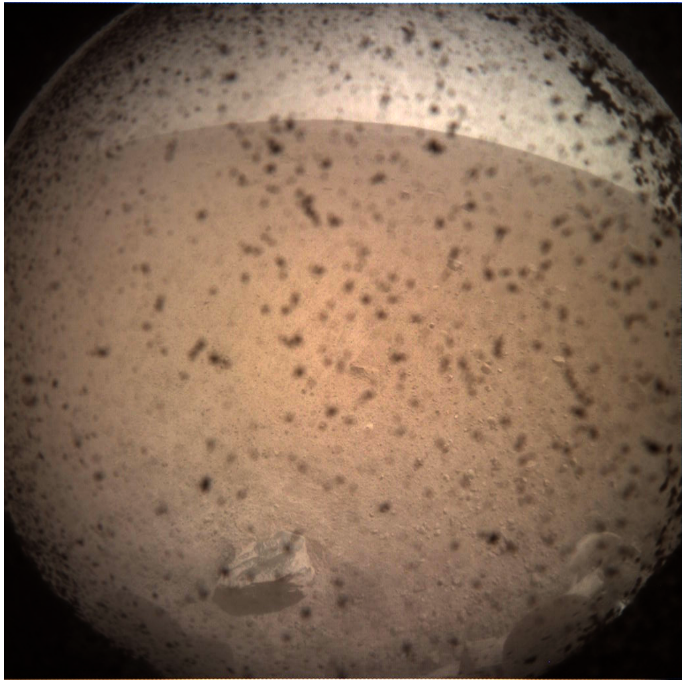
- Both MarCO-A and MarCO-B arrived at Mars and completed the relay mission

- Success depended on a few things
  - Availability of telemetry
  - Willingness of navigators to use telemetry in new ways
  - Cooperation and communication between mission control team and navigators

- Advice for future CubeSats
  - Limited platforms have limited capabilities and unique problems
  - More robust and creative usage of alternative data sources may be necessary as an alternative to large teams and continuous tracking coverage
  - Teamwork and communications always critical



First image received at JPL from InSight, via MarCO

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